# CS 425 / ECE 428
# Distributed Systems
# Fall 2019

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*Lecture 18: Mutual Exclusion*

# Why Mutual Exclusion?

- Bank's Servers in the Cloud: Two of your customers make simultaneous deposits of $10,000 into your bank account, each from a separate ATM.
    - Both ATMs read initial amount of $1000 concurrently from the bank's cloud server
    - Both ATMs add $10,000 to this amount (locally at the ATM)
    - Both write the final amount to the server
    - What's wrong?

# Why Mutual Exclusion?

- Bank's Servers in the Cloud: Two of your customers make simultaneous deposits of $10,000 into your bank account, each from a separate ATM.
  - Both ATMs read initial amount of $1000 concurrently from the bank's cloud server
  - Both ATMs add $10,000 to this amount (locally at the ATM)
  - Both write the final amount to the server
  - You lost $10,000!
- The ATMs need *mutually exclusive* access to your account entry at the server
  - or, mutually exclusive access to executing the code that modifies the account entry

# More Uses of Mutual Exclusion

- Distributed File systems
  - Locking of files and directories
- Accessing objects in a safe and consistent way
  - Ensure at most one server has access to object at any point of time
- Server coordination
  - Work partitioned across servers
  - Servers coordinate using locks
- In industry
  - Chubby is Google's locking service
  - Many cloud stacks use Apache Zookeeper for coordination among servers

# Problem Statement for Mutual Exclusion

- ***Critical Section*** Problem: Piece of code (at all processes) for which we need to ensure there is at most one process executing it at any point of time.
- Each process can call three functions
  - enter() to enter the critical section (CS)
  - AccessResource() to run the critical section code
  - exit() to exit the critical section

# Our Bank Example

```
ATM1:
    enter(S);
     // AccessResource()
    obtain bank amount;
    add in deposit;
    update bank amount;
    // AccessResource() end
    exit(S); // exit
```

```
ATM2:
    enter(S);
     // AccessResource()
    obtain bank amount;
    add in deposit;
    update bank amount;
    // AccessResource() end
    exit(S); // exit
```

# Approaches to Solve Mutual Exclusion

- Single OS:
  - If all processes are running in one OS on a machine (or VM), then
  - Semaphores, mutexes, condition variables, monitors, etc.

# Approaches to Solve Mutual Exclusion (2)

- Distributed system:
  - Processes communicating by passing messages

Need to guarantee 3 properties:

- Safety (essential) – At most one process executes in CS (Critical Section) at any time
- Liveness (essential) – Every request for a CS is granted eventually
- Ordering (desirable) – Requests are granted in the order they were made

# Processes Sharing an OS: Semaphores

- Semaphore == an integer that can only be accessed via two special functions
- Semaphore S=1; // Max number of allowed accessors

1. **wait(S)** (or **P(S)** or **down(S)**):

enter()

```
while(1) { // each execution of the while loop is atomic
        if (S > 0) {
            S--;
            break;
        }
}
```

Each while loop execution and S++ are each atomic operations – supported via hardware instructions such as compare-and-swap, test-and-set, etc.

exit()

2. **signal(S)** (or **V(S)** or **up(s)**):

```
S++; // atomic
```

# Our Bank Example Using Semaphores

```
Semaphore S=1; // shared
ATM1:
      wait(S);
       // AccessResource()
      obtain bank amount;
      add in deposit;
      update bank amount;
      // AccessResource() end
      signal(S); // exit
```

```
Semaphore S=1; // shared
ATM2:
      wait(S);
       // AccessResource()
      obtain bank amount;
      add in deposit;
      update bank amount;
      // AccessResource() end
      signal(S); // exit
```

# Next

- In a distributed system, cannot share variables like semaphores
- So how do we support mutual exclusion in a distributed system?

# System Model

- Before solving any problem, specify its System Model:
  - Each pair of processes is connected by reliable channels (such as TCP).
  - Messages are eventually delivered to recipient, and in FIFO (First In First Out) order.
  - Processes do not fail.
    - Fault-tolerant variants exist in literature.

# Central Solution

- Elect a central master (or leader)
  - Use one of our election algorithms!
- Master keeps
  - A **queue** of waiting requests from processes who wish to access the CS
  - A special **token** which allows its holder to access CS
- Actions of any process in group:
  - enter()
    - Send a request to master
    - Wait for token from master
  - exit()
    - Send back token to master

# Central Solution

- Master Actions:
  - On receiving a request from process P*i*

    **if** (master has token)

    Send token to P*i*

    **else**

    Add P*i* to queue
  - On receiving a token from process P*i*

    **if** (queue is not empty)

    Dequeue head of queue (say P*j*), send that process the token

    **else**

    Retain token

# Analysis of Central Algorithm

- Safety – at most one process in CS
  - Exactly one token
- Liveness – every request for CS granted eventually
  - With $N$ processes in system, queue has at most $N$ processes
  - If each process exits CS eventually and no failures, liveness guaranteed
- FIFO Ordering is guaranteed, in order of requests received at master

# Analyzing Performance

Efficient mutual exclusion algorithms use fewer messages, and make processes wait for shorter durations to access resources. Three metrics:

- ***Bandwidth***: the total number of messages sent in each *enter* and *exit* operation.
- ***Client delay***: the delay incurred by a process at each enter and exit operation (when *no* other process is in, or waiting)

  (We will prefer mostly the enter operation.)
- ***Synchronization delay***: the time interval between one process exiting the critical section and the next process entering it (when there is *only one* process waiting)

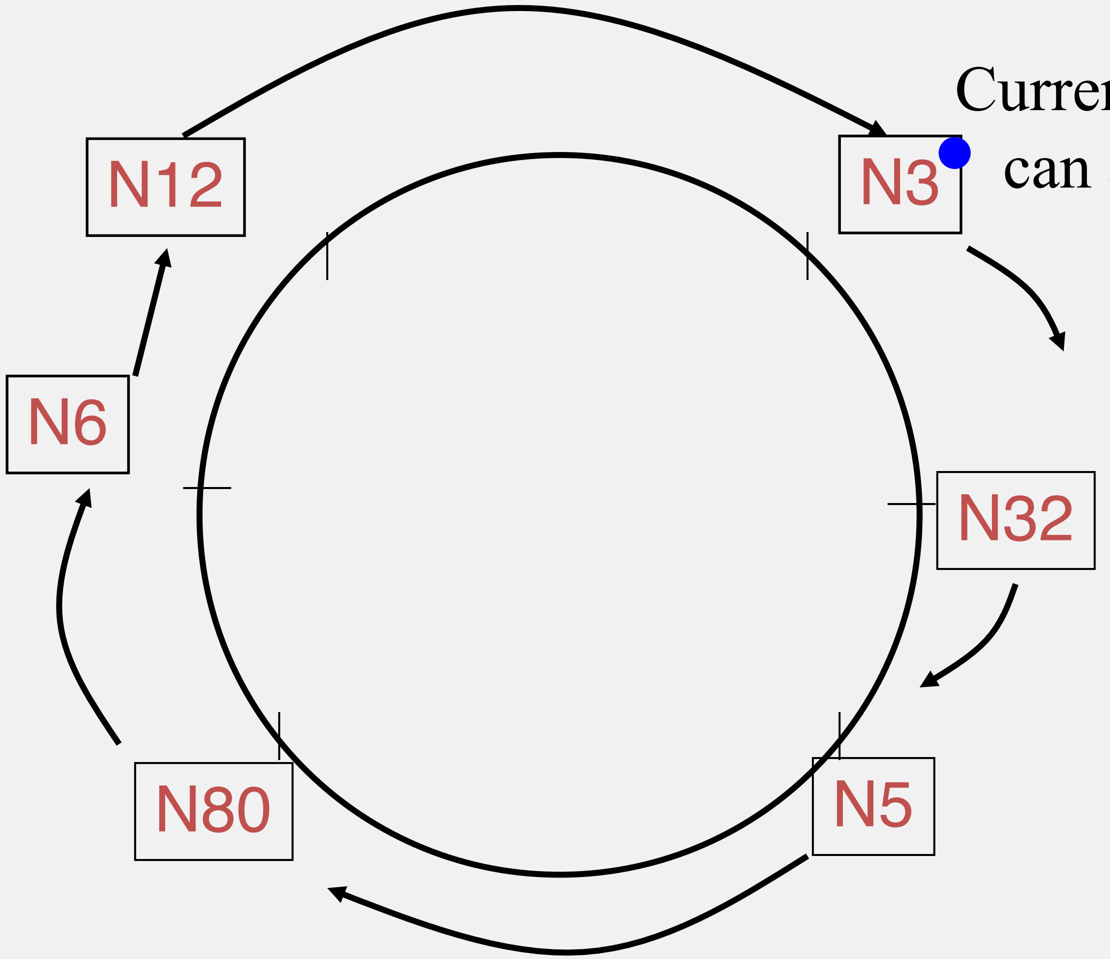
# Analysis of Central Algorithm

- ***Bandwidth***: the total number of messages sent in each *enter* and *exit* operation.
  - 2 messages for enter
  - 1 message for exit
- ***Client delay***: the delay incurred by a process at each enter and exit operation (when *no* other process is in, or waiting)
  - 2 message latencies (request + grant)
- ***Synchronization delay***: the time interval between one process exiting the critical section and the next process entering it (when there is *only one* process waiting)
  - 2 message latencies (release + grant)

# But…

- The master is the performance bottleneck and SPoF (single point of failure)

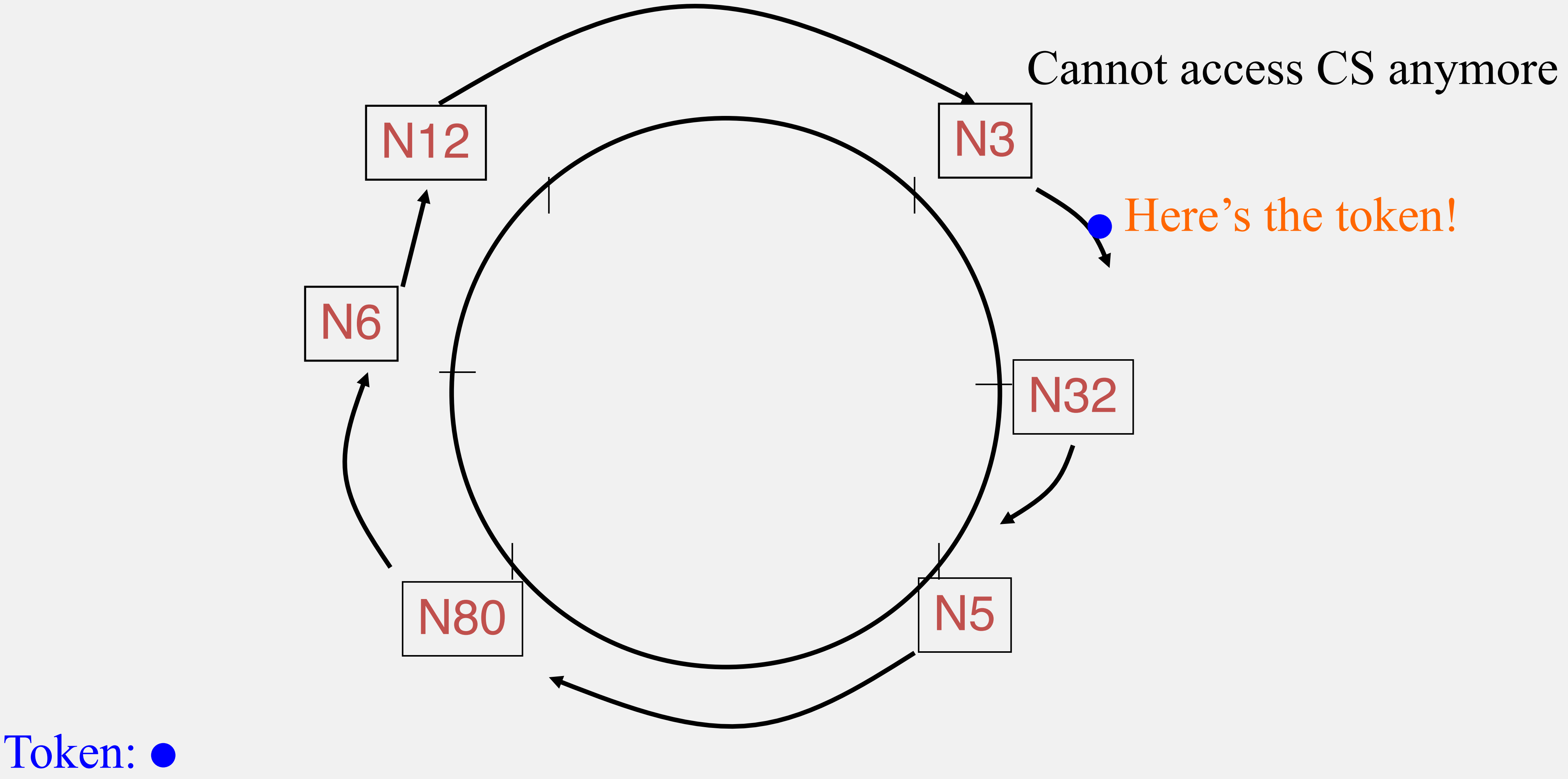
# Ring-based Mutual Exclusion



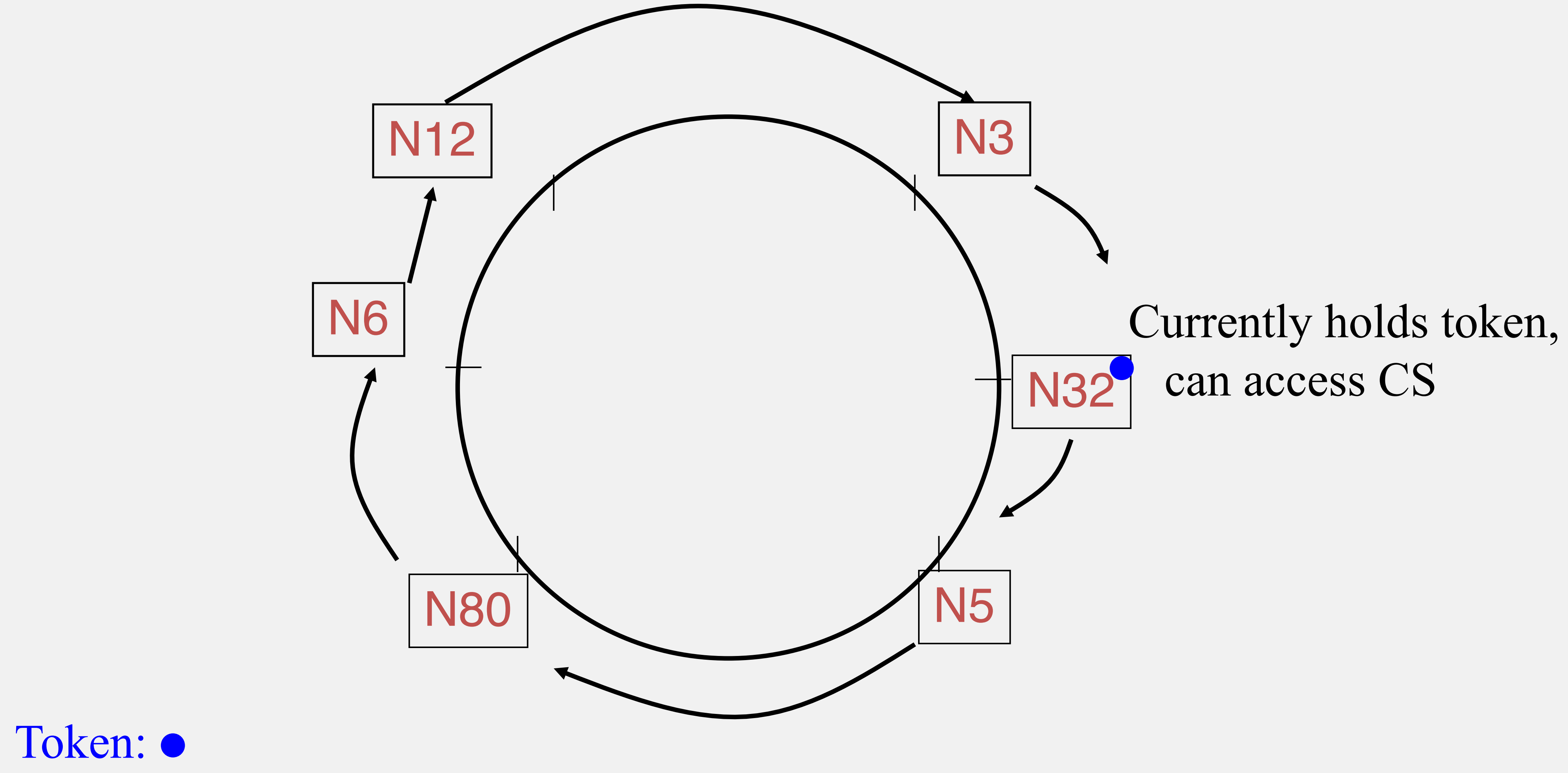

Currently holds token, can access CS

Token: ●

# Ring-based Mutual Exclusion



# Ring-based Mutual Exclusion



# Ring-based Mutual Exclusion

- *N* Processes organized in a virtual ring
- Each process can send message to its successor in ring
- Exactly 1 token
- enter()
  - Wait until you get token
- exit() // already have token
  - Pass on token to ring successor
- If receive token, and not currently in enter(), just pass on token to ring successor

# Analysis of Ring-based Mutual Exclusion

- Safety
  - Exactly one token
- Liveness
  - Token eventually loops around ring and reaches requesting process (no failures)
- Bandwidth
  - Per enter(), 1 message by requesting process but up to *N* messages throughout system
  - 1 message sent per exit()

# Analysis of Ring-Based Mutual Exclusion (2)

- Client delay: 0 to *N* message transmissions after entering enter()
  - Best case: already have token
  - Worst case: just sent token to neighbor
- Synchronization delay between one process' exit() from the CS and the next process' enter():
  - Between 1 and (*N-1*) message transmissions.
  - <u>Best case</u>: process in enter() is successor of process in exit()
  - <u>Worst case</u>: process in enter() is predecessor of process in exit()

# Next

- Client/Synchronization delay to access CS still O($N$) in Ring-Based approach.
- Can we make this faster?

# System Model

- Before solving any problem, specify its System Model:
    - Each pair of processes is connected by reliable channels (such as TCP).
    - Messages are eventually delivered to recipient, and in FIFO (First In First Out) order.
    - Processes do not fail.

# Ricart-Agrawala's Algorithm

- Classical algorithm from 1981
- Invented by Glenn Ricart (NIH) and Ashok Agrawala (U. Maryland)

- No token
- Uses the notion of causality and multicast
- Has lower waiting time to enter CS than Ring-Based approach

# Key Idea: Ricart-Agrawala Algorithm

- enter() at process P*i*
  - multicast a request to all processes
    - Request: <T, P*i*>, where T = current Lamport timestamp at P*i*
  - Wait until *all* other processes have responded positively to request
- Requests are granted in order of causality
- <T, P*i*> is used lexicographically: P*i* in request <T, P*i*> is used to break ties (since Lamport timestamps are not unique for concurrent events)

# Messages in RA Algorithm

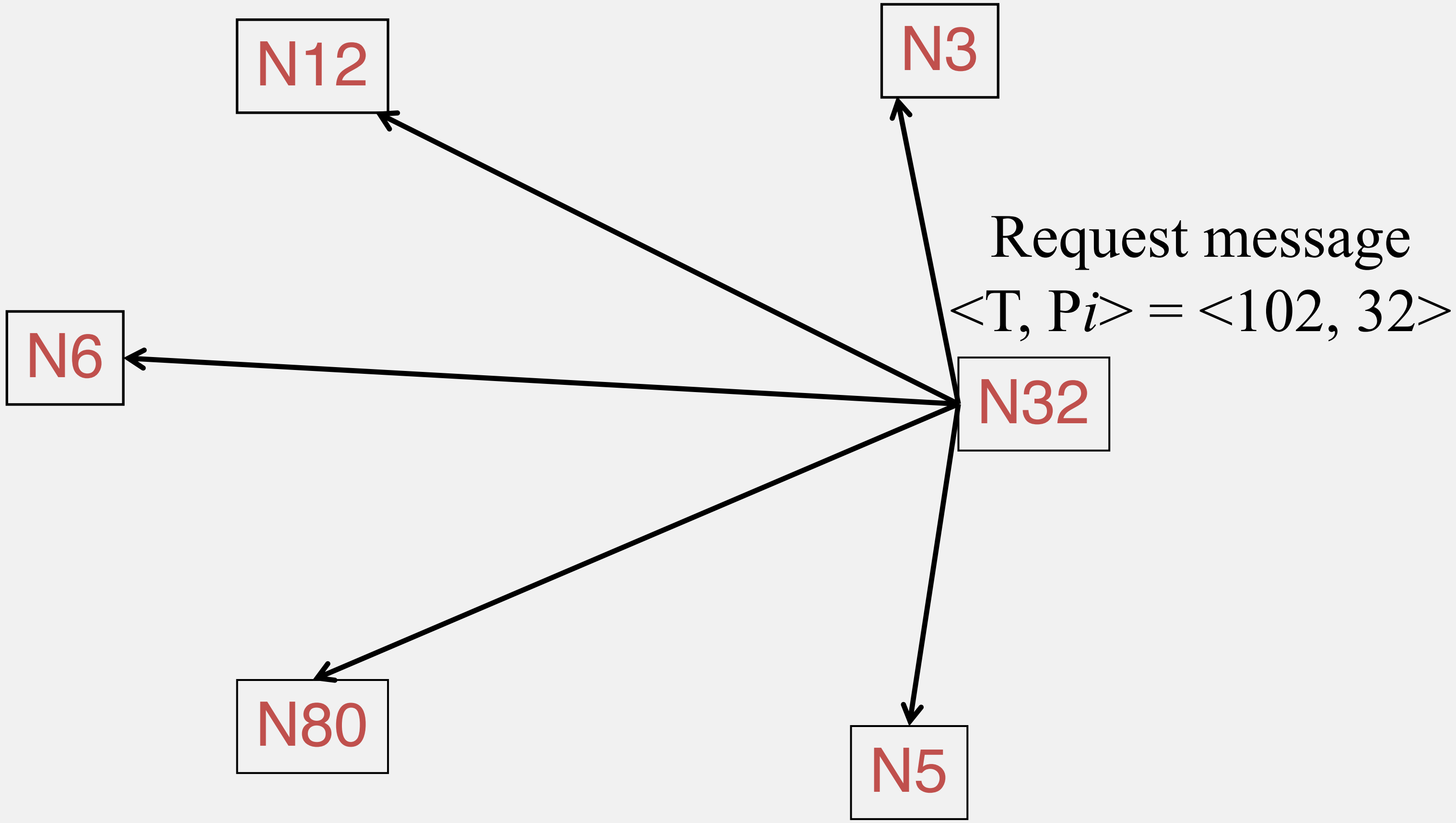
- enter() at process P$i$
  - set state to Wanted
  - multicast "Request" <T$i$, P$i$> to all processes, where T$i$ = current Lamport timestamp at P$i$
  - wait until ***all*** processes send back "Reply"
  - change state to Held and enter the CS
- On receipt of a Request <T$j$, P$j$> at P$i$ ($i \neq j$):
  - **if** (state = Held) or (state = Wanted & (T$i$, $i$) < (T$j$, $j$))

    // lexicographic ordering in (T$j$, P$j$)

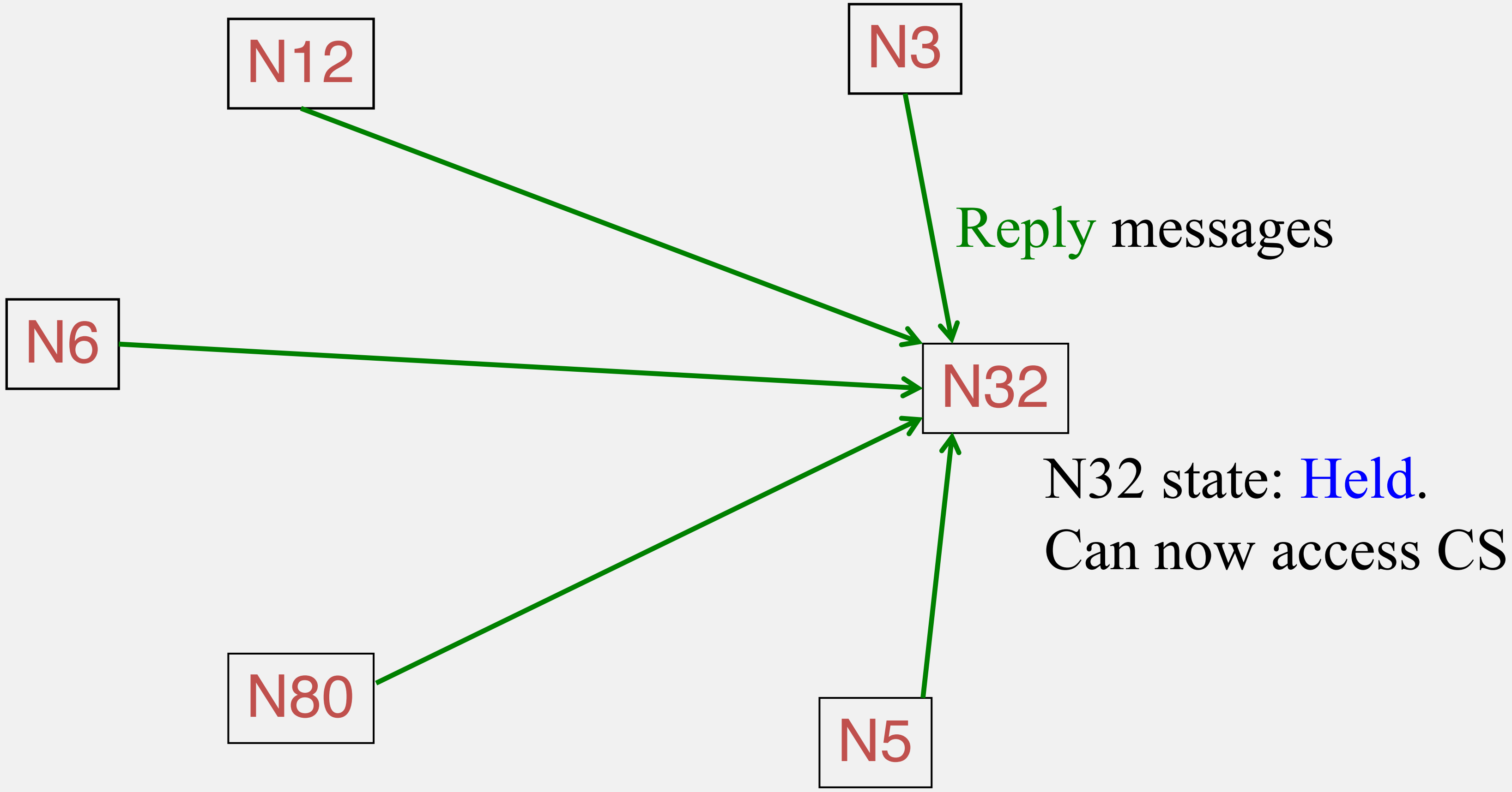
    add request to local queue (of waiting requests)

    **else** send "Reply" to P$j$
- exit() at process P$i$
  - change state to Released and "Reply" to *all* queued requests.

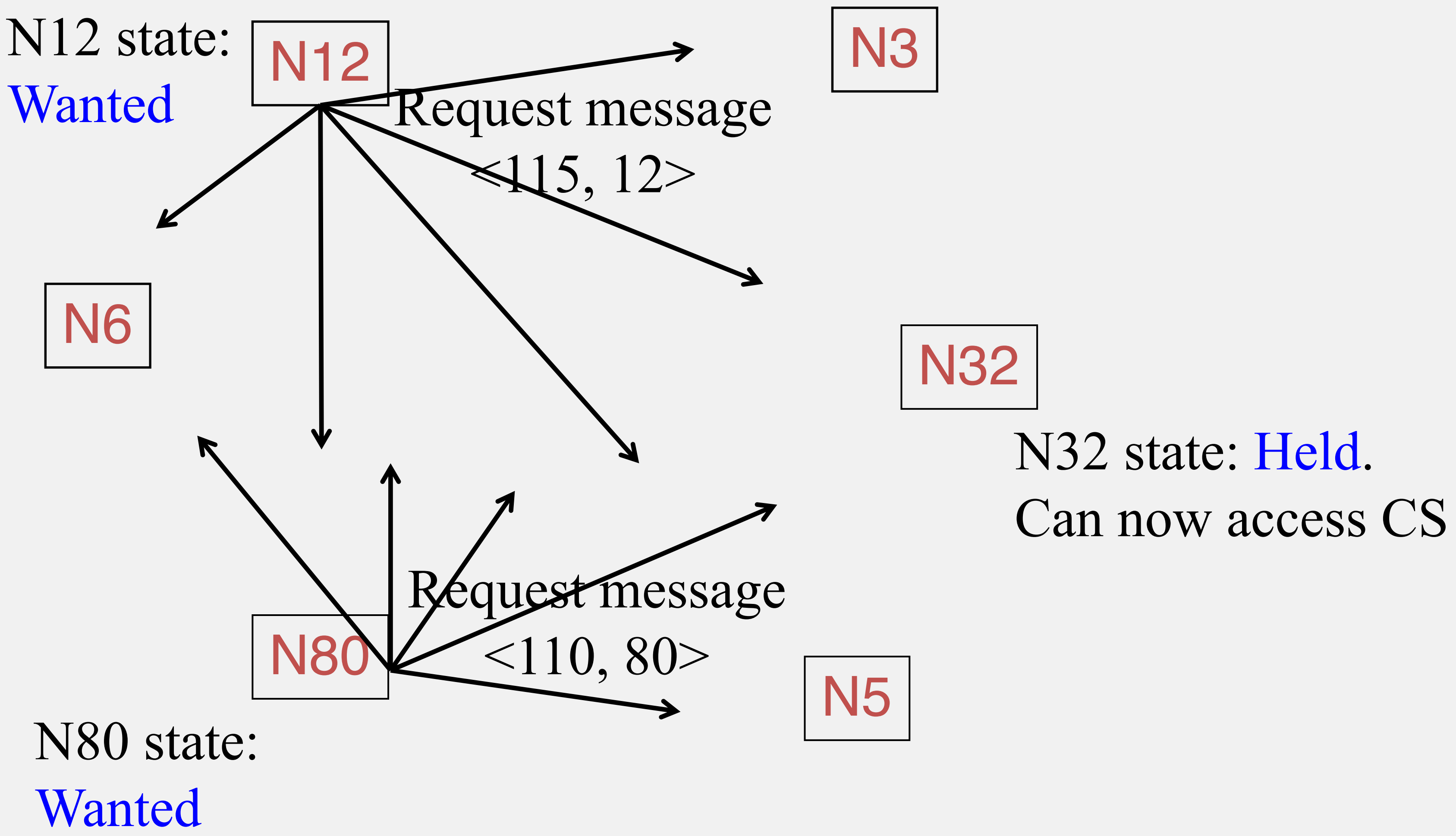
# Example: Ricart-Agrawala Algorithm



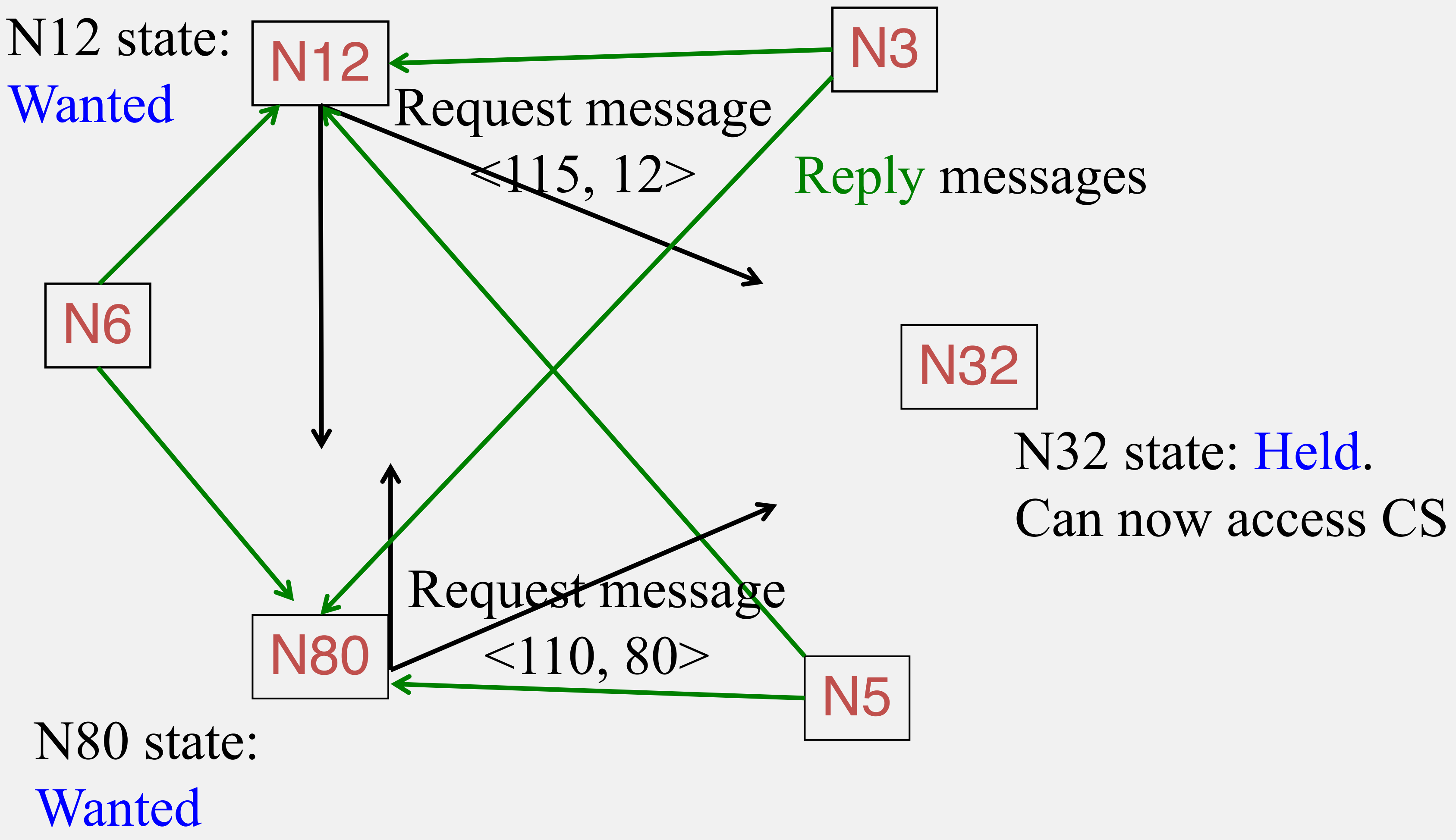
# Example: Ricart-Agrawala Algorithm



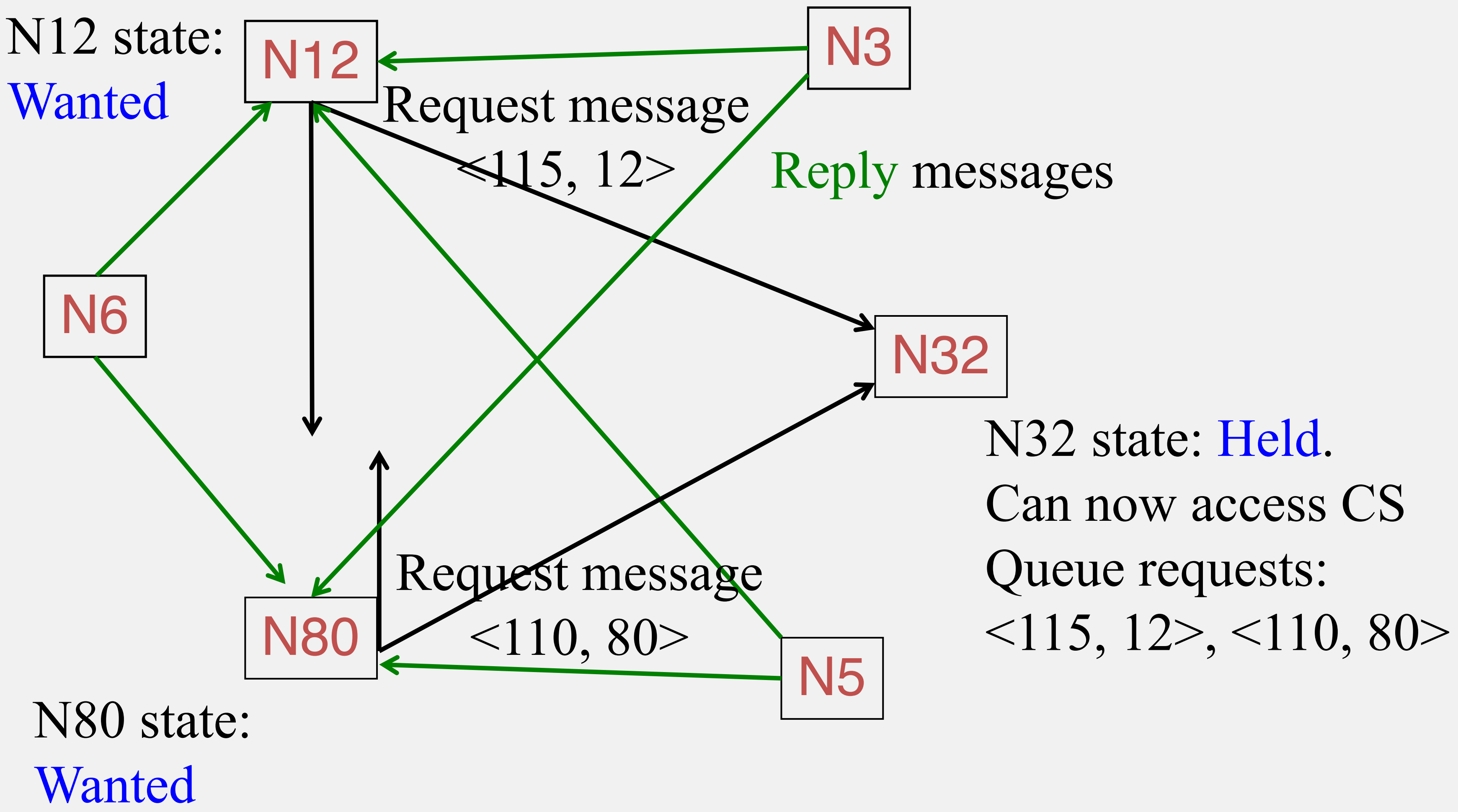
# Example: Ricart-Agrawala Algorithm



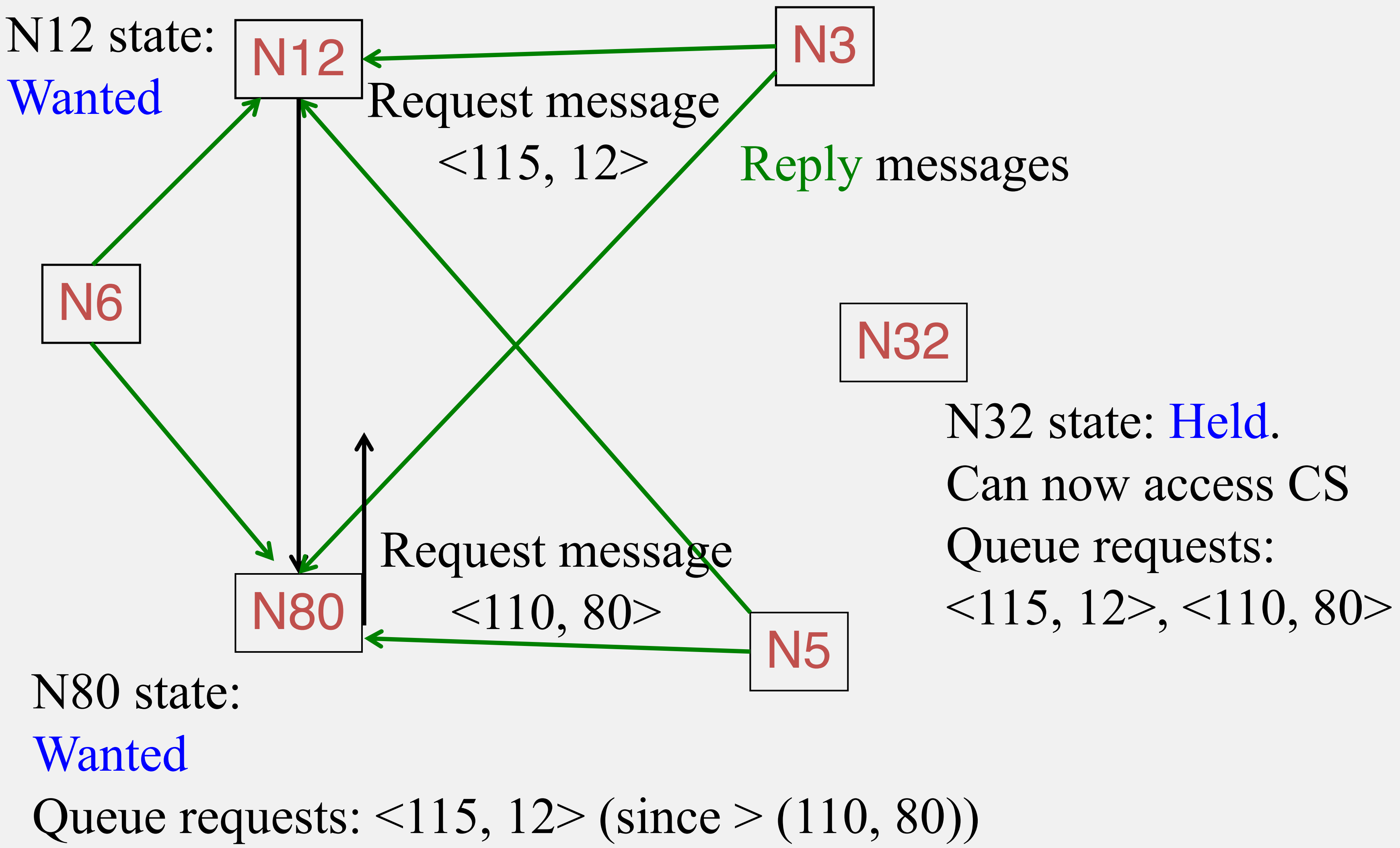
# Example: Ricart-Agrawala Algorithm



# Example: Ricart-Agrawala Algorithm

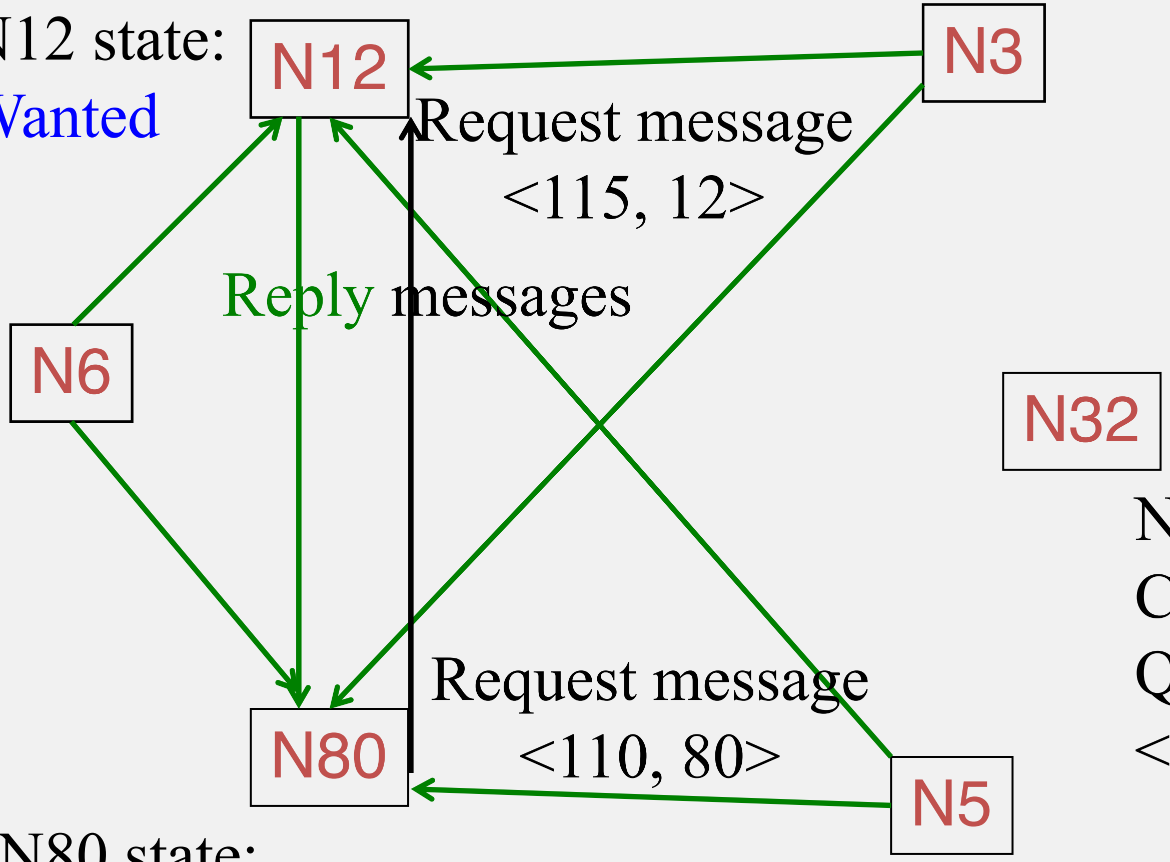


# Example: Ricart-Agrawala Algorithm



# Example: Ricart-Agrawala Algorithm

N12 state:
Wanted

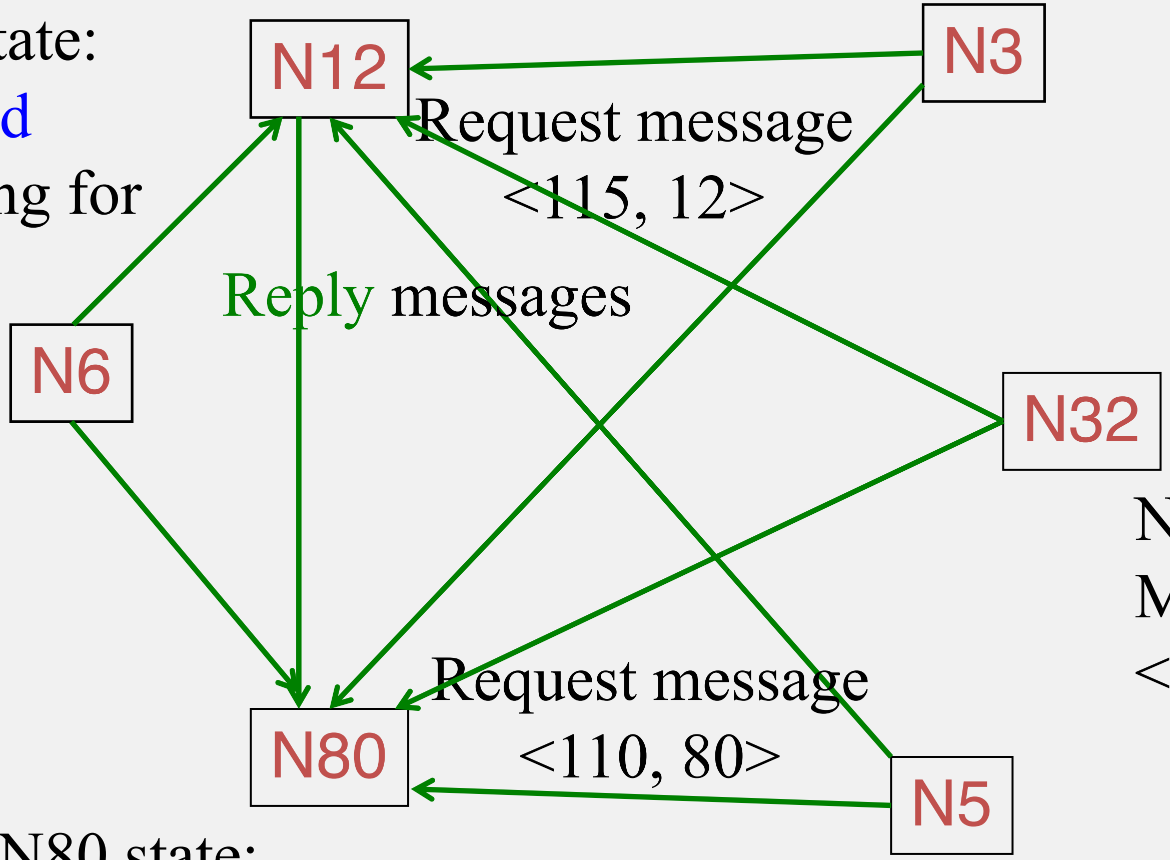



N32 state: Held.
Can now access CS
Queue requests:
<115, 12>, <110, 80>

N80 state:
Wanted
Queue requests: <115, 12>

# Example: Ricart-Agrawala Algorithm

N12 state:
Wanted
(waiting for
N80’s
reply)




N32 state: Released.
Multicast Reply to
<115, 12>, <110, 80>

N80 state:
Held. Can now access CS.
Queue requests: <115, 12>

# Analysis: Ricart-Agrawala's Algorithm

- Safety
  - Two processes P$i$ and P$j$ cannot both have access to CS
    - If they did, then both would have sent Reply to each other
    - Thus, (T$i$, $i$) < (T$j$, $j$) and (T$j$, $j$) < (T$i$, $i$), which are together not possible
    - What if (T$i$, $i$) < (T$j$, $j$) and P$i$ replied to P$j$'s request before it created its own request?
      - Then it seems like both P$i$ and P$j$ would approve each others' requests
      - But then, causality and Lamport timestamps at P$i$ implies that T$i$ > T$j$ , which is a contradiction
      - So this situation cannot arise

# Analysis: Ricart-Agrawala’s Algorithm (2)

- Liveness
  - Worst-case: wait for all other (*N*-*1*) processes to send Reply
- Ordering
  - Requests with lower Lamport timestamps are granted earlier

# Performance: Ricart-Agrawala's Algorithm

- Bandwidth: 2*(*N-1*) messages per enter() operation
  - *N-1* unicasts for the multicast request + *N-1* replies
  - *N* messages if the underlying network supports multicast (1 multicast + *N-1* unicast replies)
  - *N-1* unicast messages per exit operation
    - 1 multicast if the underlying network supports multicast
- Client delay: one round-trip time
- Synchronization delay: one message transmission time

# Ok, but …

- Compared to Ring-Based approach, in Ricart-Agrawala approach
    - Client/synchronization delay has now gone down to O(1)
    - But bandwidth has gone up to O($N$)
- Can we get *both* down?

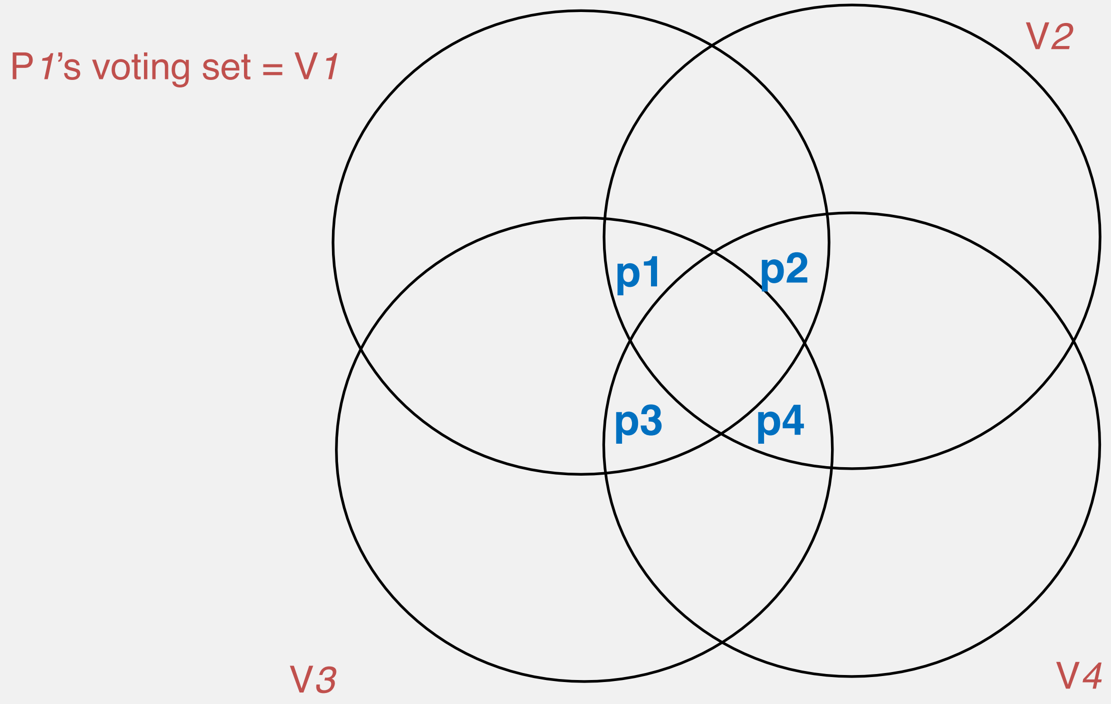
# Maekawa's Algorithm: Key Idea

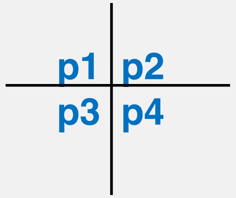
- Ricart-Agrawala requires replies from *all* processes in group
- Instead, get replies from only *some* processes in group
- But ensure that only process one is given access to CS (Critical Section) at a time

# Maekawa's Voting Sets

- Each process P$i$ is associated with a *voting set* V$i$ (of processes)
- Each process belongs to its own voting set
- *The intersection of any two voting sets must be non-empty*
  - *Same concept as Quorums!*
- Each voting set is of size $K$
- Each process belongs to $M$ other voting sets
- Maekawa showed that $K$=$M$=$\sqrt{N}$ works best
- One way of doing this is to put N processes in a $\sqrt{N}$ by $\sqrt{N}$ matrix and for each P$i$, its voting set V$i$ = row containing P$i$ + column containing P$i$. Size of voting set = $2*\sqrt{N}-1$

# Example: Voting Sets with N=4



# Maekawa: Key Differences From Ricart-Agrawala

- Each process requests permission from only its voting set members
  - Not from all
- Each process (in a voting set) gives permission to at most one process at a time
  - Not to all

# Actions

- state = Released, voted = false
- enter() at process P*i*:
  - state = Wanted
  - Multicast Request message to all processes in V*i*
  - Wait for Reply (vote) messages from all processes in V*i* (including vote from self)
  - state = Held
- exit() at process P*i*:
  - state = Released
  - Multicast Release to all processes in V*i*

# Actions (2)

- When P$i$ receives a Request from P$j$:

**if** (state == Held OR voted = true)

        queue Request

else

        send Reply to P$j$ and set voted = true

- When P$i$ receives a Release from P$j$:

**if** (queue empty)

        voted = false

else

        dequeue head of queue, say P$k$

        Send Reply *only* to P$k$

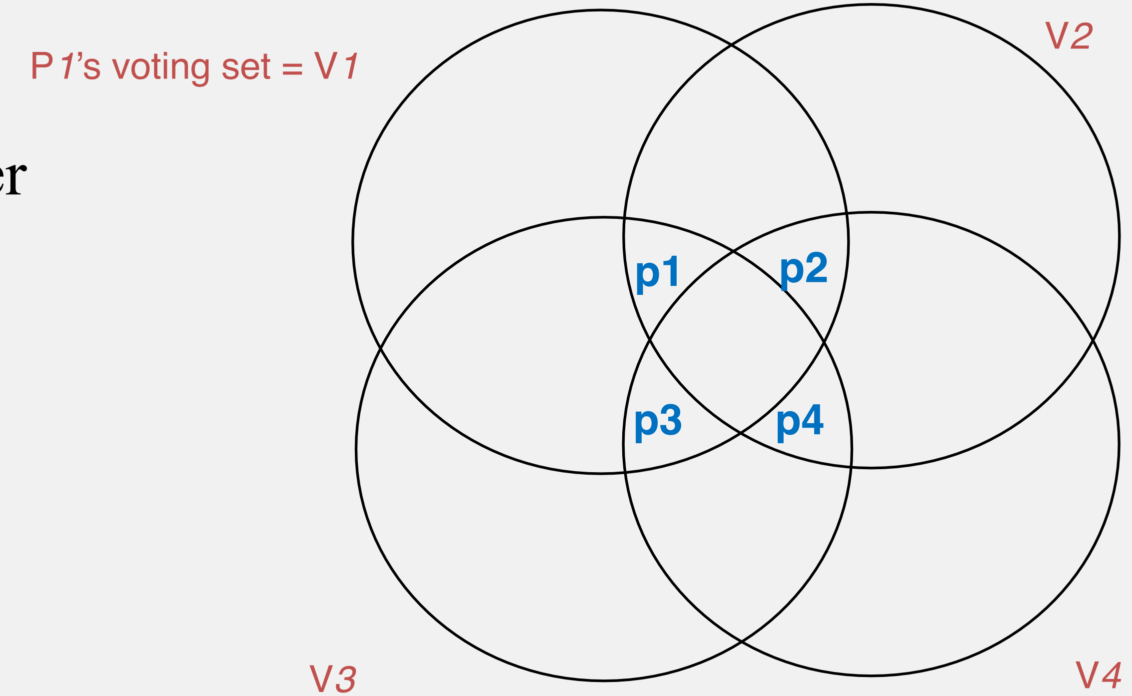
        voted = true

# Safety

- When a process P$i$ receives replies from all its voting set V$i$ members, no other process P$j$ could have received replies from all its voting set members V$j$
  - V$i$ and V$j$ intersect in at least one process say P$k$
  - But P$k$ sends only one Reply (vote) at a time, so it could not have voted for both P$i$ and P$j$

# Liveness

- A process needs to wait for at most (*N-1*) other processes to finish CS
- But does not guarantee liveness
- Since can have a *deadlock*
- Example: all 4 processes need access
  - P1 is waiting for P3
  - P3 is waiting for P4
  - P4 is waiting for P2
  - P2 is waiting for P1
  - No progress in the system!
- There are deadlock-free versions



# Performance

- Bandwidth
  - $2\sqrt{N}$ messages per enter()
  - $\sqrt{N}$ messages per exit()
  - Better than Ricart and Agrawala's ($2*(N-1)$ and $N-1$ messages)
  - $\sqrt{N}$ quite small. $N \sim 1$ million => $\sqrt{N} = 1K$
- Client delay: One round trip time
- Synchronization delay: 2 message transmission times

# Why $\sqrt{N}$ ?

- Each voting set is of size $K$
- Each process belongs to $M$ other voting sets
- Total number of voting set members (processes may be repeated) = $K*N$
- But since each process is in $M$ voting sets
  - $K*N/M = N \Rightarrow K = M$ (1)
- Consider a process P$i$
  - Total number of voting sets = members present in P$i$'s voting set and all their voting sets = $(M-1)*K + 1$
  - All processes in group must be in above
  - To minimize the overhead at each process ($K$), need each of the above members to be unique, i.e.,
    - $N = (M-1)*K + 1$
    - $N = (K-1)*K + 1$ (due to (1))
    - $K \sim \sqrt{N}$

# Failures?

- There are fault-tolerant versions of the algorithms we've discussed
  - E.g., Maekawa

- One other way to handle failures: Use Paxos-like approaches!

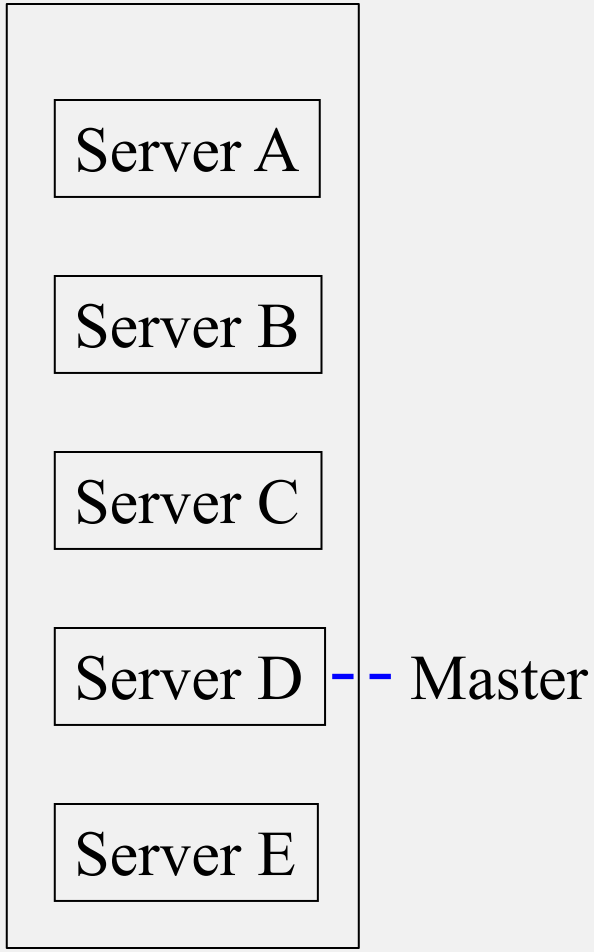
# Chubby

- Google's system for locking
- Used underneath Google's systems like BigTable, Megastore, etc.
- Not open-sourced but published
- Chubby provides *Advisory* locks only
  - Doesn't guarantee mutual exclusion unless every client checks lock before accessing resource

*Reference: http://research.google.com/archive/chubby.html*

# Chubby (2)

- Can use not only for locking but also writing small configuration files
- Relies on Paxos-like (consensus) protocol
- Group of servers with one elected as Master
  - All servers replicate same information
- Clients send read requests to Master, which serves it locally
- Clients send write requests to Master, which sends it to all servers, gets majority (quorum) among servers, and then responds to client
- On master failure, run election protocol
- On replica failure, just replace it and have it catch up



# Summary

- Mutual exclusion important problem in cloud computing systems
- Classical algorithms
  - Central
  - Ring-based
  - Ricart-Agrawala
  - Maekawa
- Industry systems
  - Chubby: a coordination service
  - Similarly, Apache Zookeeper for coordination

# Announcements

- HW3, MP3 out, due soon.
- You should have started on both by now.
- No lecture next Tuesday Oct 29 (we are ahead of our timeline)
    - Use the extra time for HW3, MP3